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On Highly Cambered Thin Circular Arcs at Low Reynolds Numbers

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- CIRCULAR ARC GEOMETRY
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BACKGROUND - SPINNAKERS



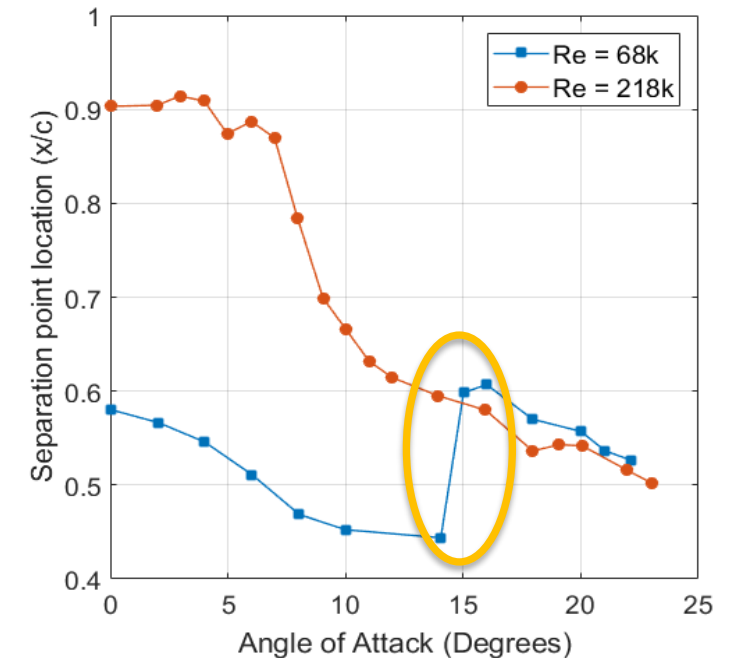
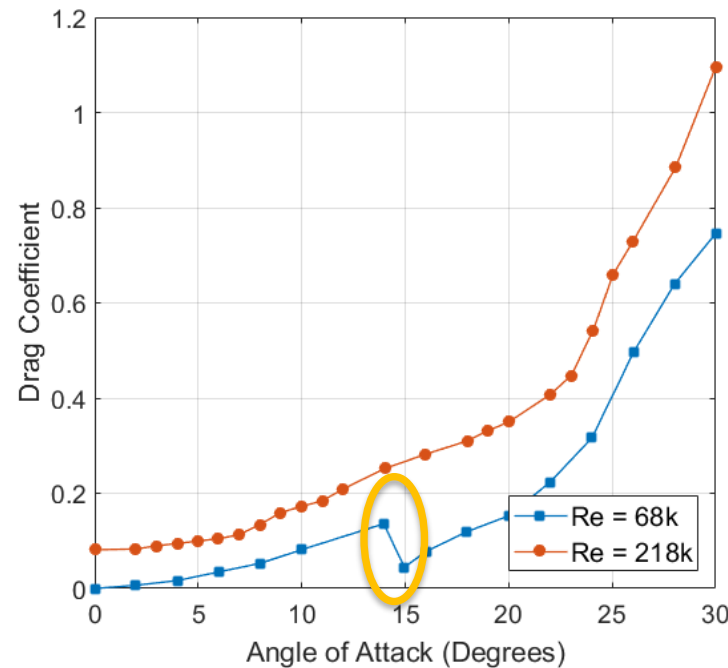
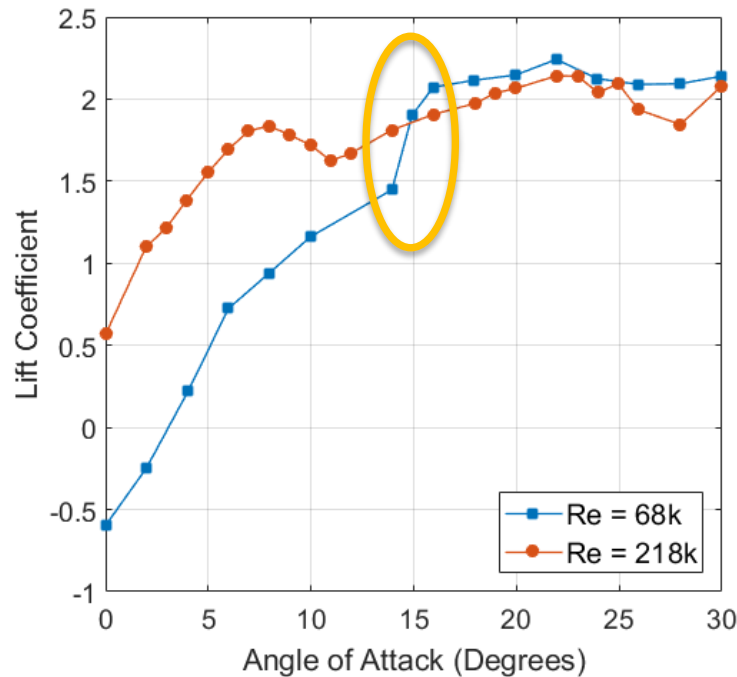
BACKGROUND - WIND TUNNEL TESTING

- Wind Tunnel assumption: the flow around the spinnaker is turbulent (at the scales typically tested in dedicated wind tunnel facilities).
- Inconsistencies noticed in the pressure distribution on wind tunnel tested models.
- Potential evidence of transition occurring in the literature.
- Highly cambered thin circular arc as a simplified cross section through a spinnaker.



CIRCULAR ARCS IN THE LITERATURE

- At low Reynolds number, evidence of a discontinuity in the lift and drag (Lombardi, 2014).
- Abrupt change in the location of the separation point at the same angle (Martin, 2015).

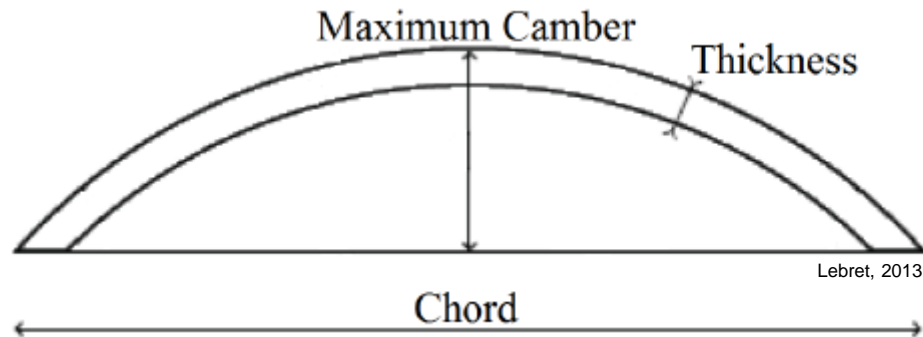


- **Hypothesis:** there is a combination of critical Reynolds Number and critical Angle of Attack that will trigger transition.

CIRCLAR ARC GEOMETRY AND MANUFACTURING

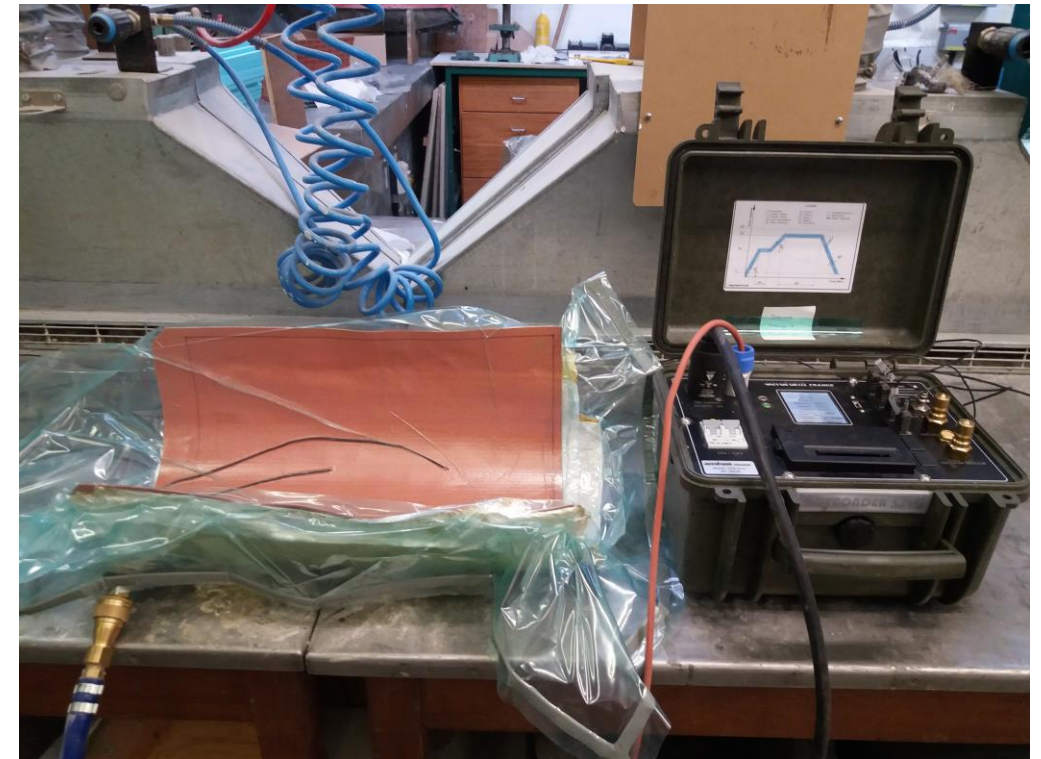
- **Specifications:**

- Highly cambered: 22.32%
- Thin: 1.8mm thick
- Chord: 200mm
- Sharp leading edge



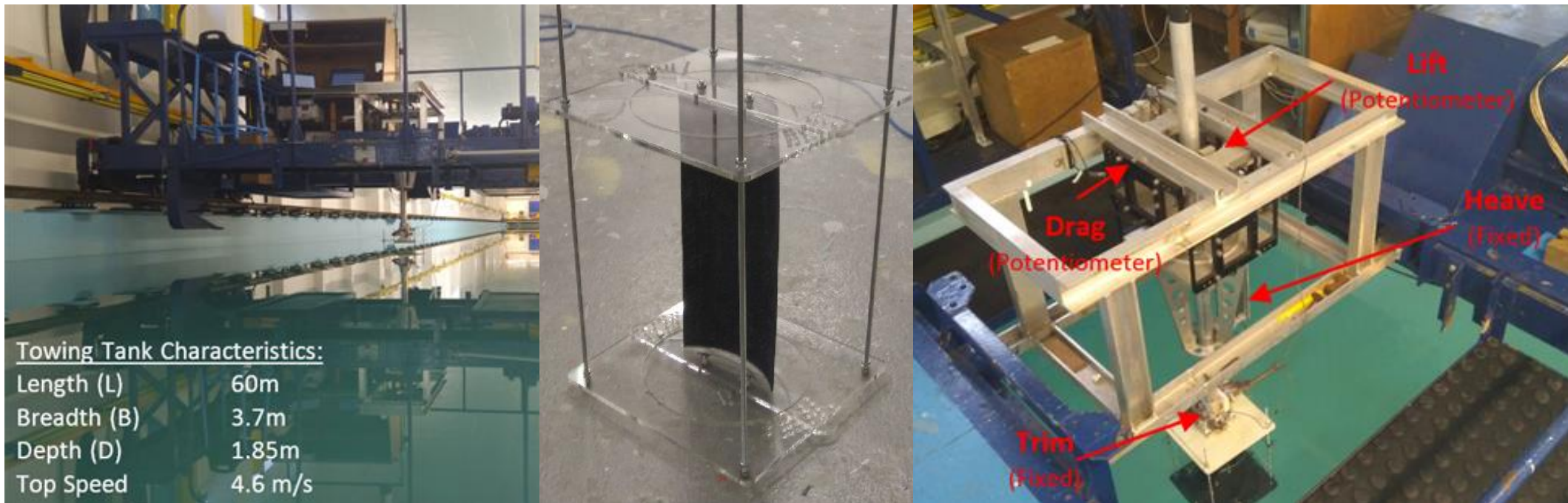
- **Manufacturing:**

- Carbon prepreg



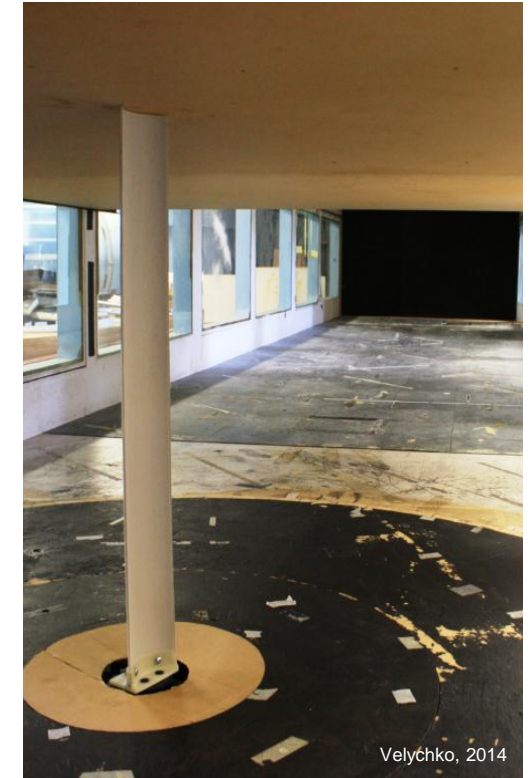
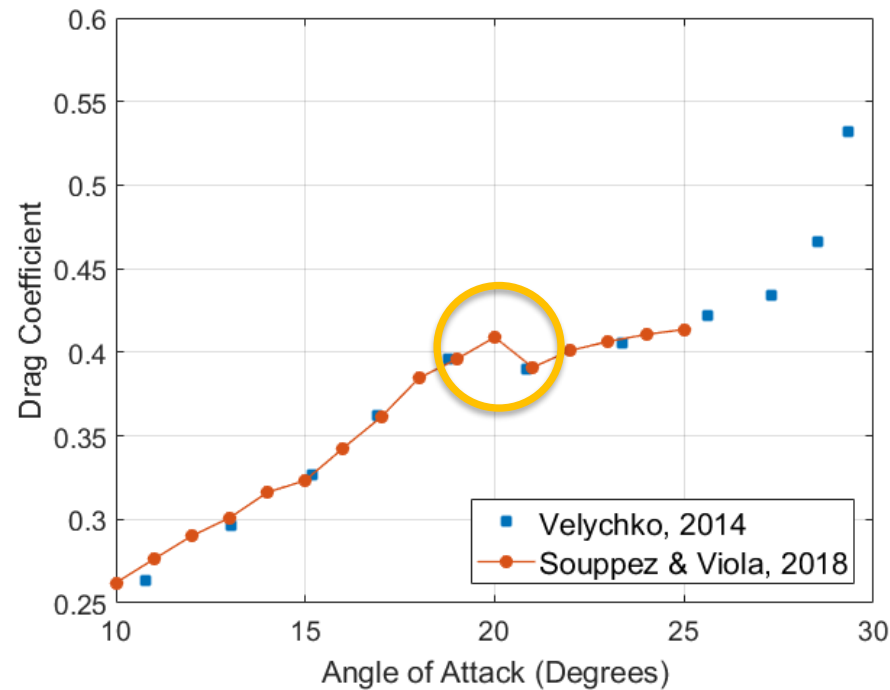
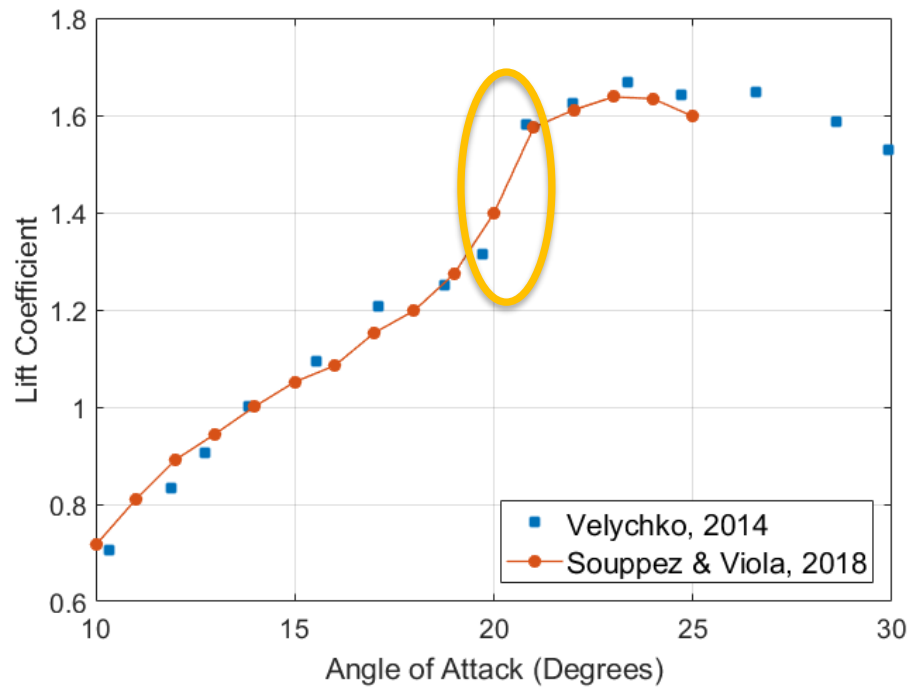
TOWING TANK EXPERIMENTAL SETUP

- Force measurements undertaken in Solent University's Hydrodynamic Test Centre:
 - Reynolds numbers: 53k, 68k, 150k and 220k
 - Angles of Attack: 5 to 20 (5 to 25 at 53k) in 1 degree increments
 - Angle of attack of 11 degrees for $130k < Re < 160k$



TOWING TANK RESULTS - $RE = 53K$

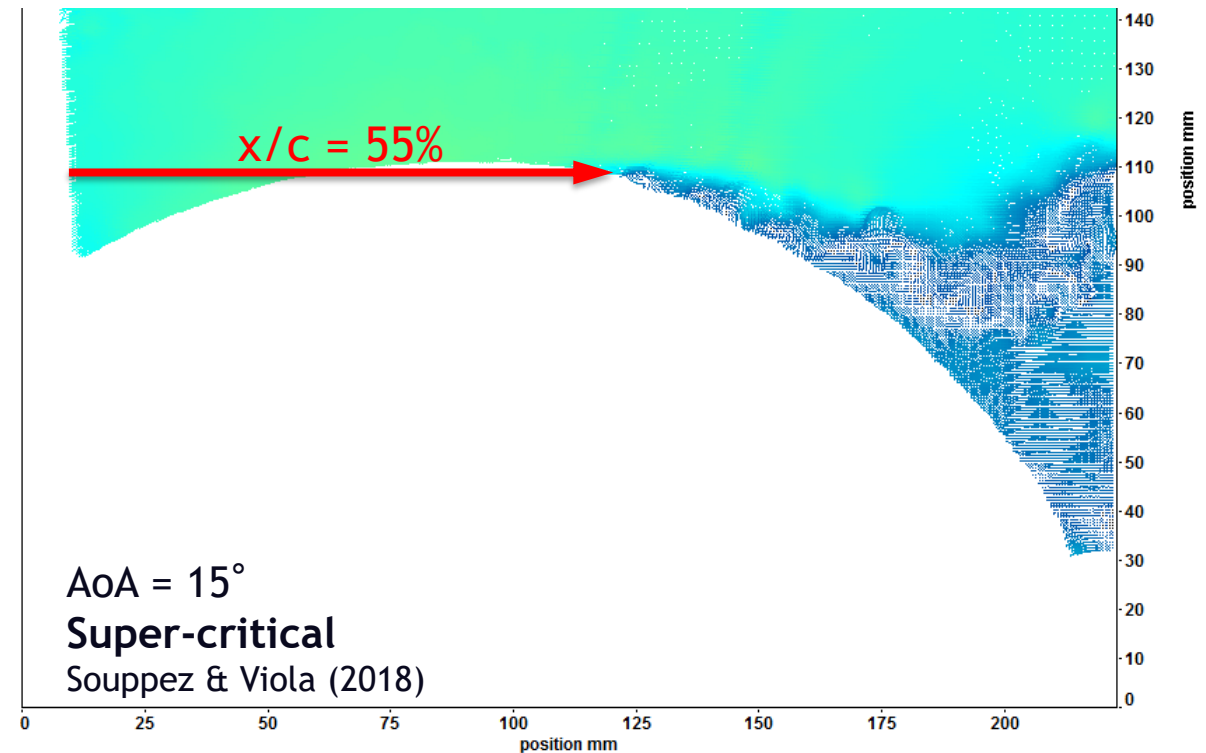
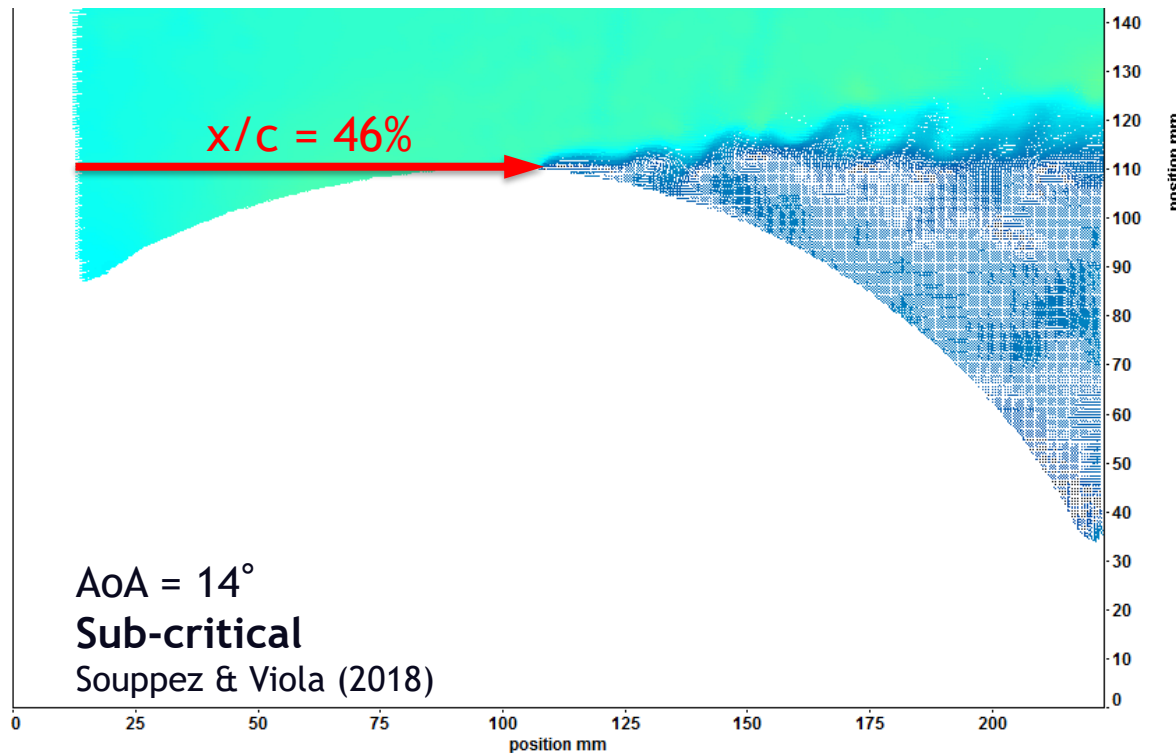
- Compared with Velychko's (2014) wind tunnel experiment.



- Good agreement between the towing tank and the wind tunnel.

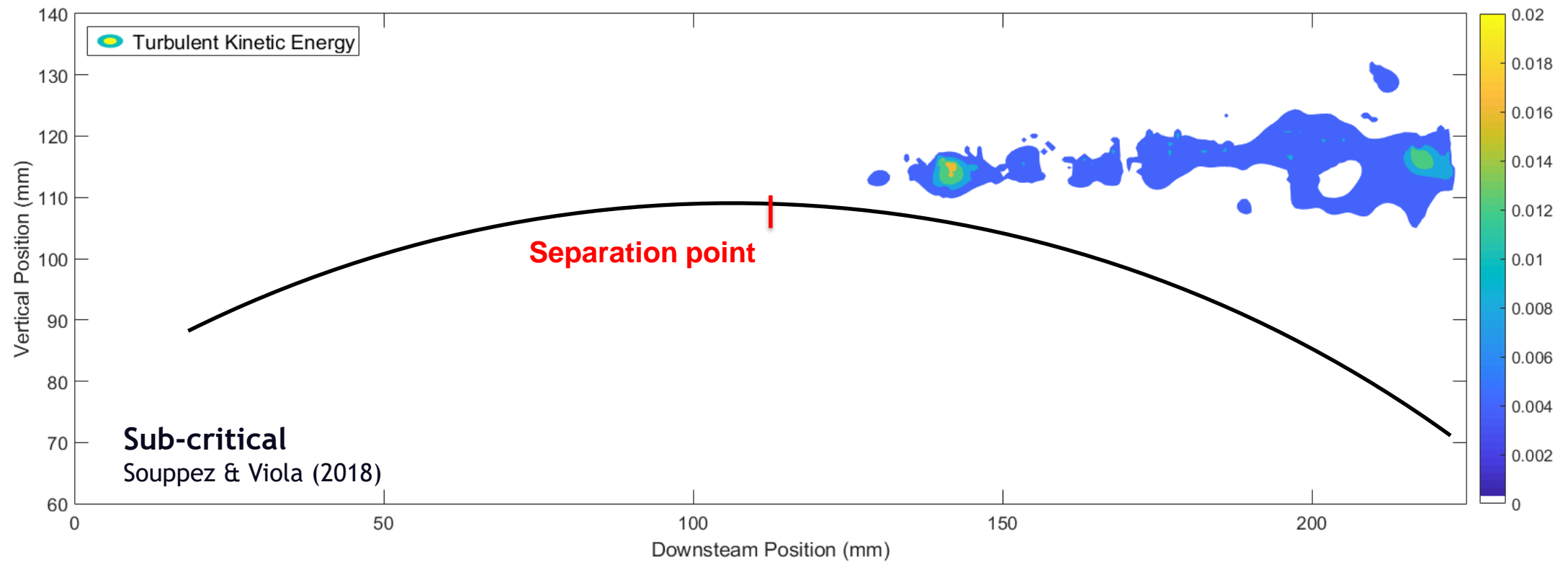
TRANSITION: SEPARATION AND WAKE SIZE - $Re = 68K$

- Delayed separation consistent with the values of Martin (2015) and reduced wake, characteristic of laminar to turbulent transition



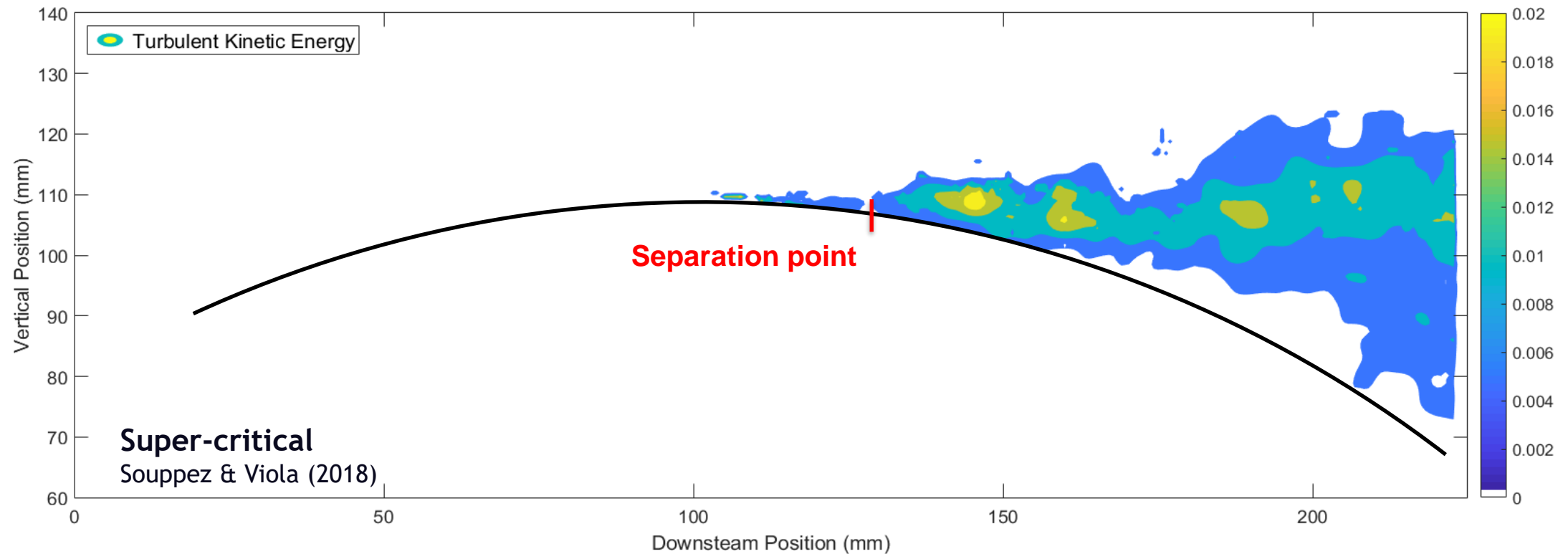
TRANSITION: TURBULENT KINETIC ENERGY - $Re = 68K$

- Further evidence of the transition can be found by computing the TKE.



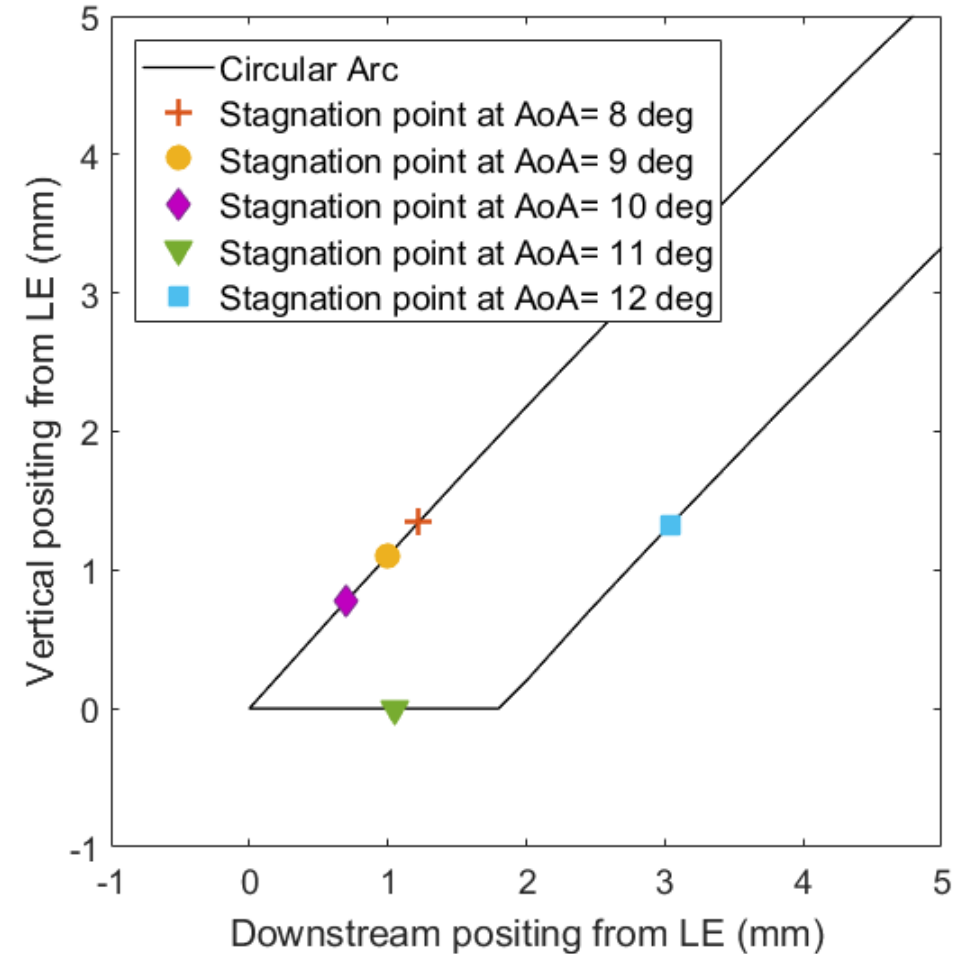
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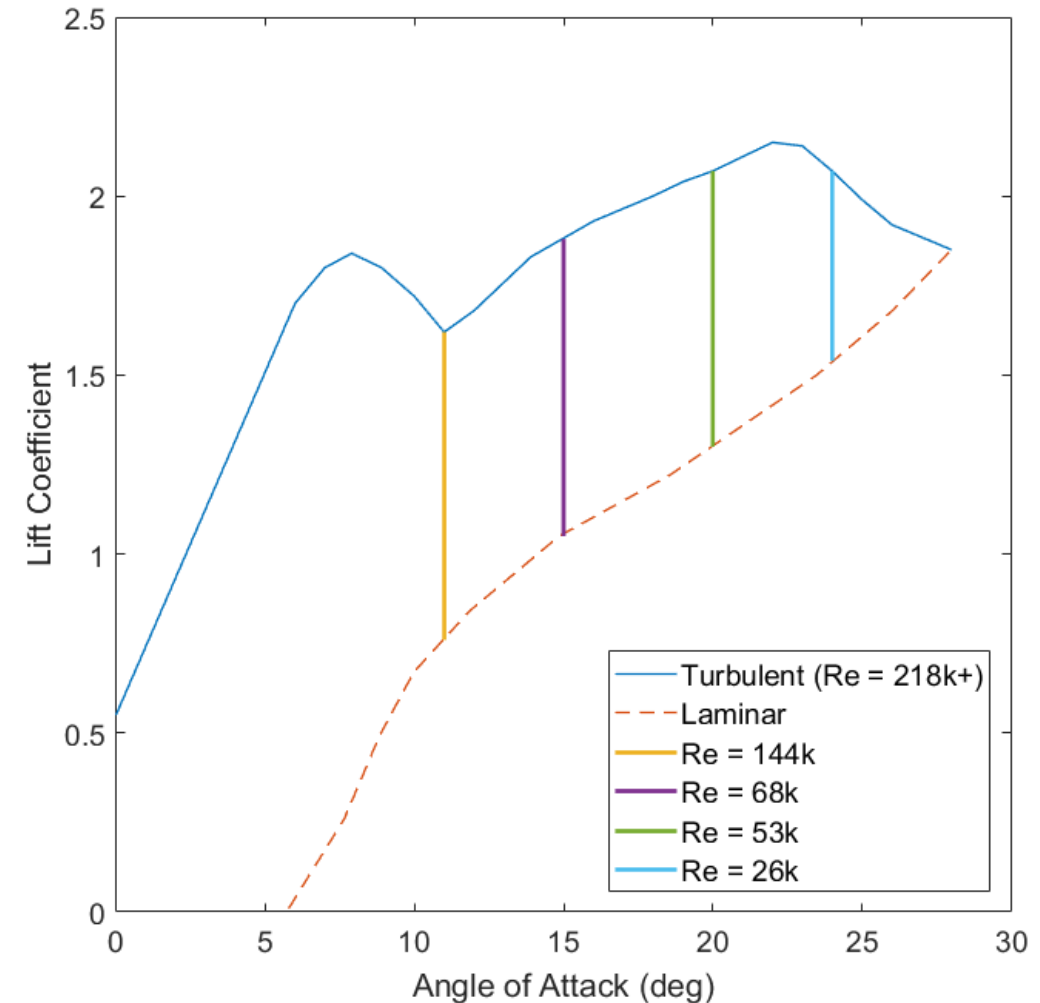
IDEAL ANGLE OF ATTACK

- PIV employed to locate stagnation points at 8, 9, 10, 11 and 12 degrees angle of attack.
- Revealed 11 degrees is the ideal angle of attack, i.e. the minimum required to inflate a soft membrane such as a spinnaker.



FINDINGS

- Below $Re = 218k$, there is a combination of Reynolds number and angle of attack that will induce transition, demonstrated with PIV.
- Ideal angle of attack occurs at 11 degrees, with a critical Reynolds number of 144k.
- Idealised model for the lift coefficient of highly cambered thin circular arcs.
- Offers a new interpretation of the data gathered in previously tested yacht sails.
- Challenges current knowledge and practice in Wind Tunnel Testing of downwind yacht sails.





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Thank You

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